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14. ABSTRACT

Ultra-high-pressure (UHP) technology as well as compressed air foam (CAF) and combined agent fire fighting systems (CAFFS)have proven to enhance the performance of fire fighting equipment using water and aqueous film forming foam(AFFF). UHP systems are capable of producing small water droplets at high velocity. As droplet size is reduced, surface area relative to mass increases, improving heat transfer. Smaller droplets however, experience greater drag, reducing throw distance. Findings indicate that on average, 150m/s exit plane velocities result in maximum throw distances of between 4600 and 5600 orifice diameters. UHP prototype and full-scale testing conducted from 2004 to 2006 found that exit plane velocities of 150m/s were found to produce 90–100mm droplets, sizes considered optimal for fire extinguishment. In addition, UHP systems were able to extinguish two-dimensional fuel fires ranging in area from 81.6 to 613.8m^2 using one-third the agent when compared to baseline AFFF tests, and one-tenth the NFPA 403 standard.

15. SUBJECT TERMS

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Potential impacts of ultra-high-pressure (UHP) technology on NFPA Standard 403

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Abstract

Ultra-high-pressure (UHP) technology as well as compressed air foam (CAF) and combined agent firefighting systems (CAFFS) have proven to enhance the performance of firefighting equipment using water and aqueous film forming foam (AFFF). UHP systems are capable of producing small water droplets at high velocity. As droplet size is reduced, surface area relative to mass increases, improving heat transfer. Smaller droplets however, experience greater drag, reducing throw distance. Findings indicate that on average, 150 m/s exit plane velocities result in maximum throw distances of between 4600 and 5600 orifice diameters. UHP prototype and full-scale testing conducted from 2004 to 2006 found that exit plane velocities of 150 m/s were found to produce 90–100 μm droplets, sizes considered optimal for fire extinguishment. In addition, UHP systems were able to extinguish two-dimensional fuel fires ranging in area from 81.6 to 613.8 m^2 using one-third the agent when compared to baseline AFFF tests, and one-tenth the NFPA 403 standard.

Keywords: Aqueous film forming foam (AFFF); Aircraft rescue and firefighting (ARFF); NFPA Standard 403

1. Introduction

Ultra-high-pressure (UHP) technology has proven to enhance the performance of firefighting equipment designed to meet *NFPA Standard 403 for Aircraft Rescue and firefighting Services at Airports*. UHP systems are capable of producing small water droplets at high velocity. As droplet size is reduced, surface area relative to mass increases, improving heat transfer. Smaller droplets however, experience greater drag, reducing throw distance. Research at the University of Florida on prototype UHP systems suggests that on average, 150 m/s exit plane velocities (76.6 bar, 0.74C_d) produce optimal throw distances of between 4000 and 5000 orifice diameters. Furthermore, exit plane velocities of 150 m/s were found to produce 90–100 μm droplets, sizes considered optimal for fire extinguishment. Full-scale testing of 265–385 L/min (70–100 gpm) UHP systems by the US Air Force (USAF) have proven to reduce water-aqueous film forming foam (AFFF) agent quantities 2–3 times over conventional water-foam systems on 325–480 m^2 (3500–5200 ft^2) hydrocarbon fuel fires. These and other findings indicate that UHP may hold the potential to improve fire suppression performance and use less agents when compared to conventional water-AFFF systems for aircraft rescue and firefighting (ARFF) equipment such as the P-19 and P-23 apparatus. As a result, UHP technology may cost-effectively address the firefighting challenges posed by a rapidly evolving large frame and composite aircraft fleet.

2. Background

2.1. NFPA Standard 403

The first meeting of the Rescue and Firefighting Panel (RFFP) was convened by the International Civil Aviation Organization (ICAO) in Montreal, Canada, in March 1970. The Panel unanimously agreed that a "critical area" should serve as the basis for calculating the quantities of

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extinguishing agents necessary to achieve fire protection within an acceptable period of time for aircraft rescue and firefighting. NFPA 403 distinguishes between the theoretical critical area (TCA) within which it might be necessary to control a fire, and a practical critical area (PCA) that is representative of actual aircraft accident conditions (Fig. 1). The theoretical area is the area adjacent to an aircraft in which fire must be controlled for the purpose of ensuring temporary fuselage integrity and providing an escape area for aircraft occupants. The TCA is defined as the area of a rectangle having as one dimension the overall length of the aircraft, and the other dimension determined by the following:

(1) For aircraft with an overall length of less than 20 m (65 ft), 12 m (40 ft) plus the width of the fuselage.
(2) For aircraft with an overall length of 20 m (65 ft) or more, 30 m (100 ft) plus the width of the fuselage.

A study comparing the actual amount of water used for foam at 106 accidents found that in 99 cases (93%), the amounts recommended by the Panel were in excess of those required in the actual aircraft accident. In light of this, the Panel decided to use two-thirds of the TCA as the PCA [1].

NFPA 403 also provides guidance for determining the quantities of extinguishing agents to be applied to the critical area by the time necessary to control and extinguish the fire. The quantity of agent, application rate and equipment and techniques to be used should be capable of controlling the fire in the PCA in 1 min, and, should be capable of extinguishing the fire, or at least maintaining conditions that do not pose a threat to life in the PCA for an additional minute until rescue operations are completed [1]. These agent quantities are known as "Q_1" and "Q_2" respectively. An application rate of 5.29 L/m^2 (0.13 gal/sf) within the PCA is generally required for water and 3% AFFF, although the total amount of water and foam may vary depending on the size of the aircraft, number of passengers and fuel load.

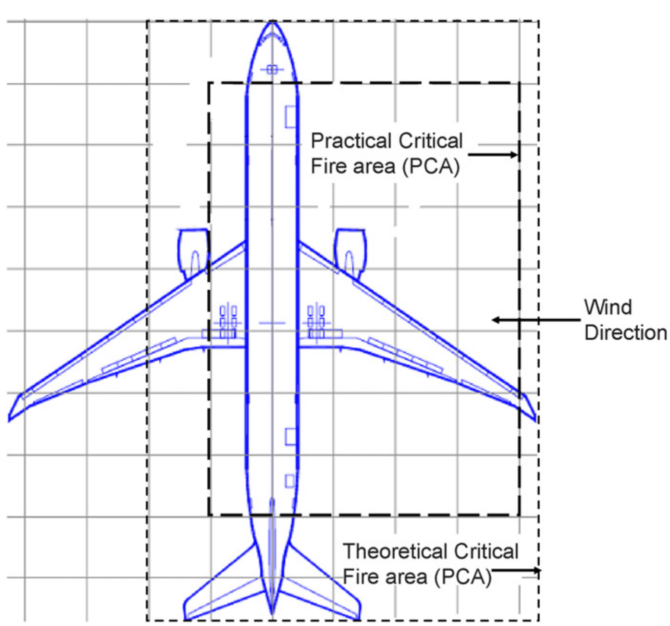

Fig. 1. NFPA 403 Standard theoretical critical area (TCA) and practical critical area (PCA).

2.2. UHP technology development

In its current form, the NFPA 403 Standard has survived from its origins in 1970 to the present with only minor revisions. With the introduction of the Airbus A380 and the composite Boeing 787, aircraft expected to serve both civilian and military roles, added firefighting capabilities will likely be needed to meet NFPA Standard 403. In response, The US Air Force Research Laboratory (AFRL) has developed UHP firefighting systems that have demonstrated extinguishment of fires using less than one-third the amount of agent used by conventional distribution systems. Research has found that efficacy, or how efficient a suppression system extinguishes a fire, is in part related to water droplet size and velocity. Smaller droplets have greater surface area relative to mass. As a result, smaller droplets are able to transfer more heat and hold the potential to provide extinguishment with significantly less water. However, smaller particles experience greater friction or "drag" with the surrounding air, limiting their throw distance and ability to penetrate into the combustion zone of a fire. In addition, discharge velocities needed to produce smaller droplets require higher discharge pressures, limiting system footprint and cost reductions achieved by flow reduction.

As part of this effort, the University of Florida has characterized high-pressure (48–210 bar), low-flow (3.9–23.3 L/min) water streams to predict optimal throw distance and droplet size. This research is being used to develop optimal system specifications for a variety of scaleable applications, including P-19 and P-23 aircraft crash rescue and firefighting equipment. Successful demonstration and implementation of UHP technology may significantly improve firefighting effectiveness while reducing agent, equipment footprint and cost.

3. Experimental methods and procedures

3.1. Droplet size

Testing was first conducted on a miniaturized 3.9 L/min (1.0 gpm) constant volume UHP system to observe changes in particle size relative to discharge velocity. Five (5) round jet nozzles ranging in orifice size from 0.66 to 0.97 mm (0.026–0.038 in) inside diameter (ID) were attached to a 6.5 mm (0.25 in) diameter supply hose. A straight, rigid section of pipe approximately 60 cm (24 in) in length was installed between the supply hose and the nozzle. A Malvern/INSITEC In-Line Ensemble Particle Concentration and Size (EPCS) system was used to measure downstream particle size distributions. Particle size measurements were taken every 25 cm (10 in) from the exit plane of the nozzle to a distance of 250 cm (100 in). Measurements were taken along the centerline stream and 1.25 cm (0.5 in) above and 1.25 cm (0.5 in) below the centerline. Stream particle size distribution measurements were terminated at a distance where the spray began to transform into indiscernible mist. Ambient conditions such as lighting and airflow were controlled to reduce experimental error among tests. Downstream particle velocities were observed using high-speed digital photography.

3.2. Throw distance

Additional testing was conducted on a second miniaturized 3.9–23.3 L/min (1.0–6.0 gpm) variable volume UHP system to observe changes in throw distance relative to discharge velocity. Five (5) additional round jet nozzles ranging in orifice size from 1.19 to 2.49 mm (0.047–0.10 in) ID were tested. Maximum throw distance was determined by observing the distance from the exit plane of the nozzle where either the droplet fallout from the stream began to occur under the influence of gravity or, the distance the spray region of stream terminated into indiscernible, momentum-free mist.

3.3. Suppression efficacy

A 270–390 L/m (70–100 gpm) UHP system, along with compressed air foam (CAF) and combined agent firefighting systems (CAFFS) experimental technologies, were evaluated using 81.6 m^2 (877 sf), 325.5 m^2 (3500 sf), 483.6 m^2 (5200 sf), and 613.8 m^2 (6600 sf) hydrocarbon fuel fires on water and gravel at Tyndall AFB, Florida. The largest test size (613. 8 m^2) is roughly one-third less than the NFPA 403 PCA for the Boeing 737–400 and Airbus A320. Hydrocarbon fuels (Jet-A/JP-8) were ignited on water to provide a uniform, two-dimensional (2D) surface and to avoid destruction of testing surfaces and containment linings. Residual fuel, agent and other contaminants were pumped to a nearby fuel–water separator for reclamation. Hydrocarbon fuels were also ignited on gravel extending approximately 2.5 cm (1.0 in) above the water to provide an irregular, three-dimensional (3D) surface. Steel rings were used to create the four fire sizes. To avoid biases introduced by human factors such as varying levels of operator skill and experience, P-19, UHP, CAF and CAFFS systems and personnel were randomly changed between tests. However, changing surfaces and fire sizes between tests was considered time and resource prohibitive. A 30 s "pre-burn" was initiated prior to each test to allow the fire to become fully involved. Fuel remaining after each test was re-ignited to allow both residual fuel and agent to burn off prior to commencing subsequent tests.

The equipment chosen to provide a "baseline" standard for full-scale testing was the P-19 apparatus (Fig. 2). The P-19 is the standard apparatus used for both civilian and military ARFF worldwide. The P-19 baseline was provided using 3% AFFF at flow rates of approximately 970–1940 L/min (250–500 gpm). As the first of three experimental technologies tested, the UHP system (Fig. 3), delivered 6% AFFF solution at approximately 270–385 L/min (70–100 gpm) and 104 bar (1500 psi) measured at the discharge side of the pump. Exit plane pressures were calculated to be approximately 83 bar (1200 psi), slightly higher than pressures considered optimal from prototype development and testing. The CAF system technology injected compressed air into the pressurized line between the pump and the nozzle at approximately 485–850 L/min (125–220 gpm). This resulted in a higher expansion ratio of 3% AFFF solution at the nozzle exit plane. The aspirated foam generated by the CAF system increased agent surface area and coverage, theoretically providing better cooling and insulation between the fuel and the fire.

The CAFFS system technology also injected CAF (3%) in the same manner as the CAF systems, but added the benefits of potassium bicarbonate base dry chemical.

Fig. 2. P-19 water-foam (3% AFFF) baseline apparatus.

A special nozzle was used that discharged the dry chemical through a central orifice at 1.4–3.4 kg/s (3.0–7.5 lb/s). The CAF discharged through an annular opening around the dry chemical orifice. Water-foam and dry chemical were discharged simultaneously and continuously. Both CAF and CAFFS technologies were tested using a modified P-27 apparatus (Fig. 4). For all tests, vehicles were stationary and forward turrets were used to deliver the agent. Tests were conducted using available equipment at flow rates and discharge pressures that were within the capabilities of the equipment. Tests were conducted with wind speeds of 11 km/h (7 mph) or less approaching $\pm 30^{\circ}$ from the rear of the vehicle.

4. Results

4.1. Droplet size vs. discharge velocity

Discharge velocities and pressures for five (5) round jet nozzles ranging in orifice size from 0.66 to 0.97 mm (0.026–0.038 in) were calculated for 3.9 L/min (1.0 gpm) constant flow rate and a 0.74 discharge coefficient (provided by manufacturer). Discharge pressures and velocities were verified by gauge readings and high-speed digital photography. Droplet sizes generated by 0.66–0.97 mm (0.026–0.038 in) nozzles ranged from 32.9 to 143.7 μm. Mean centerline droplet sizes ranged from approximately 50 to 120 μm at corresponding discharge velocities of between 115 and 249 m/s, respectively (Fig. 5). Within this range, the relationship between droplet size and discharge velocity was roughly linear. As a result, a change in velocity produced an inversely proportional change in droplet size. 0.81 mm (0.032 in) and 0.89 mm (0.035 in) nozzles with discharge velocities of 137 m/s (440f/s) and 166 m/s (551f/s) respectively, produced mean droplet sizes between 90 and 100 μm. Smaller nozzles (0.66–0.74 mm) with higher discharge velocities (198–249 m/s) produced mean droplet sizes of 70 μm and less. The largest nozzle (0.97 mm) with the lowest discharge velocity (115 m/s) produced mean droplet sizes of 120 μm.

Fig. 3. Water-foam (6% AFFF) UHPS apparatus.

Fig. 4. P-27 water-foam (3% AFFF) and dry-chemical CAFFS apparatus.

Tests using 60 cm^2 (9 in^2) *N*-heptane fuel fires within an enclosed 5.7 m^3 (200 ft^3) test chamber were commissioned by AFRL to ADA Associates in 1994 to determine optimal fire suppression droplet sizes. Results showed that nozzles generating droplets of approximately 100 μm at flow rates between 2.9 and 4.7 L/min (0.8–1.2 gpm) were most effective in reaching the fuel surface, cooling the combustion reaction and diluting the oxygen being delivered to the fire. Droplets less than 100 μm were less able to reach the combustion zone. Droplets greater than 100 μm were less able to transfer heat away from the combustion reaction [2].

4.2. Throw distance vs. discharge velocity

Discharge velocities and pressures for five (5) additional round jet nozzles ranging in orifice size from 1.19 to 2.49 mm (0.047–0.10in) were calculated for 3.9–23.3 L/min (1.0–6.0 gpm) variable flow rates. For 1.19–1.78 mm (0.047–0.070 in) nozzles, throw distances were maximized at discharge velocities of approximately 150 m/s (492 f/s). Results seem to indicate a decrease in discharge velocities necessary to achieve optimal throw distance for larger nozzles as evidenced by the apparent shift to the left in the plots presented in Fig. 6. However, the *rate* of decrease in velocity necessary to achieve optimal throw distance between 1.45 and 1.78 mm nozzles is roughly one-fourth that of the decrease between 1.19 and 1.45 mm nozzles, suggesting that optimal throw distances may be asymptotic at 120–130 m/s discharge velocity for larger nozzles. For 1.19–1.78 mm (0.047–0.070 in) nozzles, maximum throw distance at approximately 76.6 bar (1110 psi) discharge pressure and 150 m/s (492 f/s) discharge velocity declines from approximately 5600 orifice diameters until asymptotic at approximately 4500 orifice diameters.

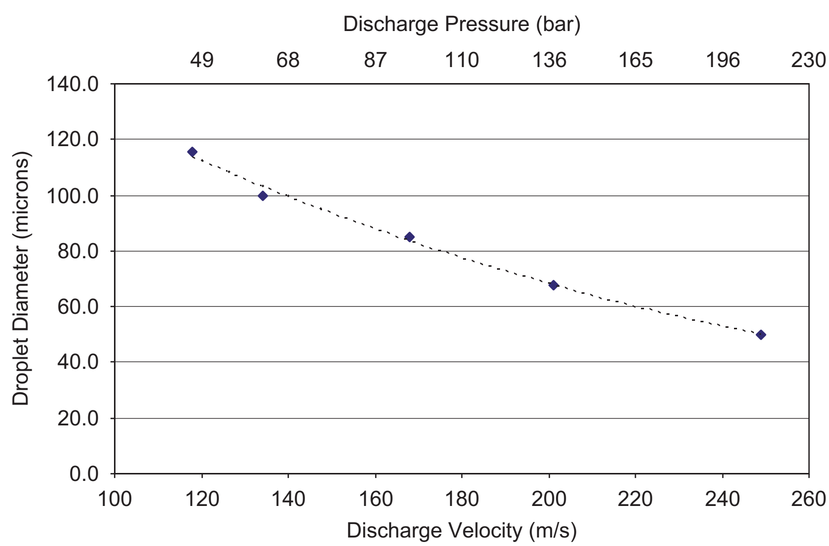

Fig. 5. Droplet size vs. discharge velocity.

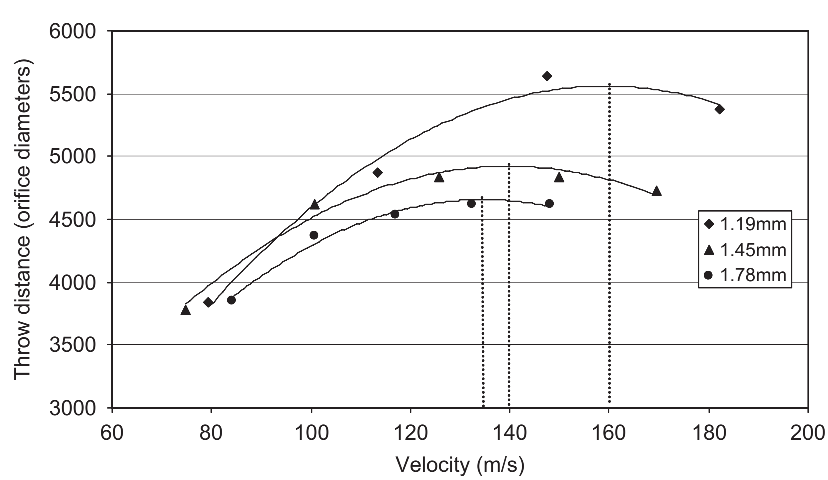

Fig. 6. Throw distance vs. discharge velocity.

4.3. Full-scale testing on uniform 2D surface (water)

A total of 114 fire tests were conducted on UHP, CAF and CAFFS experimental technologies using 81.6 m^2 (877 sf), 325.5 m^2 (3500 sf), 483.6 m^2 (5200 sf), and 613.8 m^2 (6600 sf) hydrocarbon fuel fires on water. A minimum of 20 tests were conducted on each experimental technology and the P-19 baseline standard. For the P-19 baseline, 98% of all fire sizes (2σ) on water were extinguished with 2.77 L/m^2 (0.068 gal/sf) or less of 3% AFFF and water, and required on average, an application rate of 1.79 L/m^2 (0.045 gal/sf) to achieve extinguishment. Comparatively, the UHP system required 0.80 L/m^2 (0.0196 gal/sf) or less 6% AFFF and water to extinguish 98% of all fire sizes (2σ) on water, and 0.57 L/m^2 (0.014 gal/sf) on average. CAF and CAFFS systems required 1.59 L/m^2 (0.039 gal/sf) and 1.87 L/m^2 (0.046 gal/sf) or less 3% AFFF and water to extinguish 98% of all fire sizes (2σ) on water, and 1.14 L/m^2 (0.029 gal/sf) and 1.05 L/m^2 (0.026 gal/sf) on average to achieve extinguishment, respectively (Fig. 7). Given NFPA Standard 403 requires an application rate of 5.29 L/m^2 (0.130 gal/sf) water-foam agent for ARFF, a UHP system would require 1.68 L/m^2 (0.041 gal/sf) for comparable protection (Table 1).

4.4. Full-scale testing on irregular 3D surface (gravel)

A total of 66 fire tests were conducted on UHP, CAF and CAFFS experimental technologies using 325.5 m^2 (3500 sf) and 483.6 m^2 (5200sf) hydrocarbon fuel fires on gravel. A minimum of 10 tests were conducted on each experimental technology and the P-19 baseline standard. For the P-19 baseline, 98% of all fire sizes (2σ) on gravel were extinguished with 3.80 L/m^2 (0.093 gal/sf) or less of 3% AFFF and water, and required on average, an application rate of 2.61 L/m^2 (0.064 gal/sf) to achieve extinguishment. Comparatively, the UHP system required 3.31 L/m^2 (0.081 gal/sf) or less 6% AFFF and water to extinguish 98% of all fire sizes (2σ) on gravel, and 2.20 L/m^2 (0.054 gal/sf) on average. CAF and CAFFS systems required 3.61 L/m^2 (0.089 gal/sf) and 2.80 L/m^2 (0.069 gal/sf) or less 3% AFFF and water to extinguish 98% of all fire sizes (2σ) on gravel, and 2.16 L/m^2 (0.053 gal/sf) and 1.47 L/m^2 (0.036 gal/sf) on average to achieve extinguishment, respectively (Fig. 8). Given NFPA Standard 403 requires an application rate of 5.29 L/m^2 (0.130 gal/sf) water-foam agent for ARFF, a UHP system would require 4.480 L/m^2 (0.110 gal/sf) for comparable protection (Table 2).

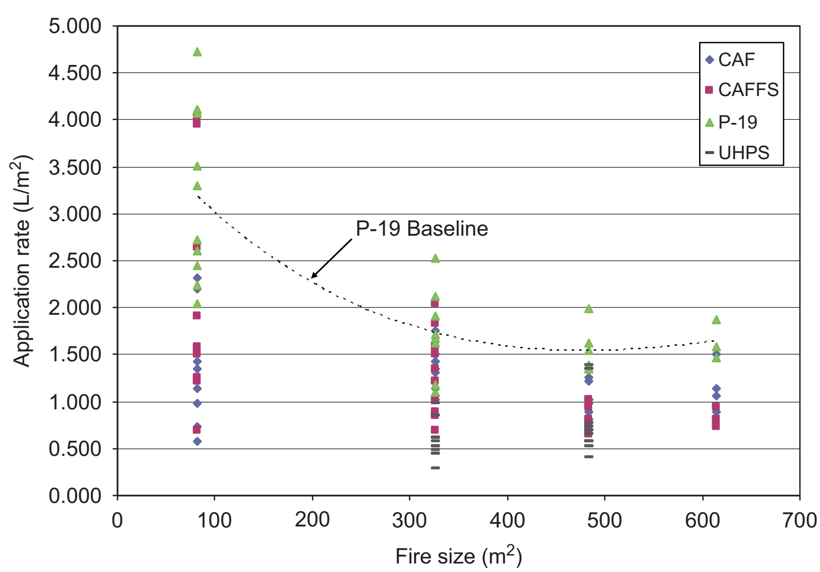

Fig. 7. Application rates (L/m^2) required for extinguishment of 81.6–613.8 m^2 hydrocarbon fuel fires on uniform 2D surface (water).

Table 1
Modified NFPA 403 critical application rates for extinguishment of 2D fuel fires on water

Technology	Number of tests	Mean application rate (L/m^2)	P-19 baseline equivalent	NFPA 403 application rate (L/m^2)[a]	Variance (2σ)
P-19	22	1.792	1.000	5.294	0.994
UHP	20	0.570	0.318	1.684	0.204
CAF	27	1.140	0.636	3.367	0.448
CAFFS	27	1.049	0.614	3.251	0.766

[a]Proposed equivalent.

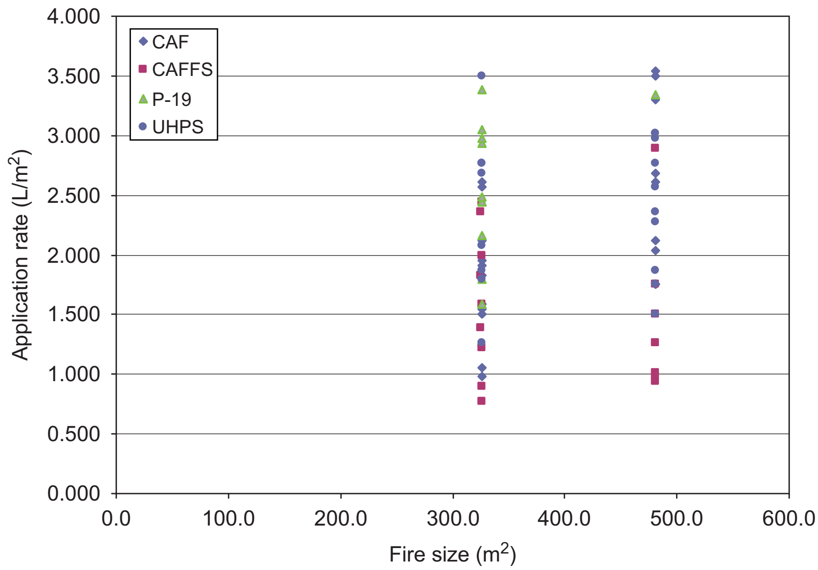

Fig. 8. Application rates (L/m^2) required for extinguishment of 81.6–613.8 m^2 hydrocarbon fuel fires on irregular 3D surface (gravel).

Table 2
Modified NFPA 403 critical application rates for extinguishment of 3D fuel fires on gravel

Technology	Number of tests	Mean application rate (L/m^2)	P-19 baseline equivalent	NFPA 403 application rate (L/m^2)[a]	Variance (2σ)
P-19	11	2.606	1.000	5.294	0.611
UHP	15	2.200	0.844	4.480	0.590
CAF	20	2.158	0.828	4.383	0.733
CAFFS	15	1.466	0.563	2.981	0.529

[a]Proposed equivalent.

Following fire extinguishment effectiveness tests, a 1165 L/min (300 gpm) UHP system was installed on a P-19 apparatus. The P-19 UHP system was designed to discharge water-foam agent through a 14 mm (0.55 in) diameter orifice with an exit plane discharge pressure of approximately 96 bar (1400 psi), a discharge velocity of approximately 170 m/s (560f/s) and a maximum throw distance of approximately 4150 orifice diameters, or 58 m (190 ft). The UHP system was observed to have a sustained maximum throw range of approximately 3930 orifice diameters or 55 m (180 ft). The small discrepancy between the predicted and actual throw distance of the 1165 L/min (300 gpm) UHP system could be attributed to ambient test conditions such as wind, different interpretations in what defines maximum throw distance, slight variances in nozzle diameter and discharge coefficient, or the gradual relative decline in throw distance (in terms of orifice diameters) as the size of nozzle increases as previously discussed.

5. Conclusions

Prototype UHP test results indicate that 150 m/s (492 f/s) exit plane velocities and 76.6 bar (1110 psi) exit plane pressures on average, result in maximum throw distances of between 4600 and 5600 orifice diameters, although optimal discharge velocity appears to decrease slightly for larger orifices. Furthermore, exit plane velocities of approximately 150 m/s were found to produce 90–100 μm droplets, sizes considered optimal for fire extinguishment from previous AFRL studies. Full-scale testing indicates that UHP systems are capable of achieving extinguishment on 325–480 m^2 (3500–5200 ft^2) hydrocarbon pool fires with 3.2 times less water-foam agent than the P-19 baseline standard and roughly half the agent of the next best experimental technology. Because of such low agent quantities, a 6% AFFF water-foam agent was required for the UHP system (twice the AFFF concentration used for all other experimental technologies and the P-19 baseline) to provide adequate “burn back” protection. In spite of this, the UHP system used approximately 40% less total AFFF solution. UHP systems however, were found to be less effective on gravel fuel fires, achieving extinguishment with only a 20% reduction in water-foam agent. The CAFFS technology achieved superior performance on gravel fires where the film forming ability of AFFF was reduced and the 3D extinguishment capabilities of dry chemical became the presiding factor.

Preliminary research and testing shows that UHP as well as CAF/CAFFS technologies hold the potential to improve fire suppression performance and use less agent when compared to conventional water-AFFF systems for aircraft crash rescue and firefighting equipment such as the P-19 and P-23 apparatus. Such improvements in advanced firefighting technology such as UHP, once thoroughly validated, may be factored into the agent quantity requirements of the NFPA Standard 403 for Aircraft Rescue and Firefighting Services at Airports to reduce equipment footprint, personnel requirements and costs.

6. Limitations

Although full-scale testing offers the most realistic evaluation of how an experimental technology may perform in the field, several factors contributed to variance in the test data. As shown (Fig. 7), variance or ''scatter'' in the test data is greatest for smaller fire sizes. In addition, extinguishment efficiency improves proportionately to increases in fire size. Observations revealed the existence of a ''time constant'' for the turret operator to target and engage the fire. Although evident in all tests, this unproductive time constant was proportionately larger for smaller fires, resulting in greater data scatter and higher agent application rates (L/m^2) necessary to achieve extinguishment. Other human factors potentially biasing test results include the experience gained from repetitive testing and altering of firefighting technique during the test sequence. The data shows a relative improvement in extinguishment efficiency and a reduction in variance as the test series progressed, indicating that test personnel had become more consistent and effective as they gained experience. For example, firefighters initially used the ''rain drop'' technique during the early fires, as they were trained. As they gained experience, they learned that applying agent at the base of the fire was more effective and resulted in faster extinguishment. In addition, agent application variance among personnel was evident. Uncontrollable factors, such a wind, humidity and temperature may have also introduced some variance between tests, although none were statistically significant.

The NFPA 403 standard agent application rate of $5.92\,L/m^2$ (0.130 gpm) referenced in this research was used to establish a performance baseline for the experimental technology testing herein. Application of the NFPA 403 standard to actual airport fire protection requirements must consider passenger and cargo load, fuel capacity and many other factors.

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[1] National Fire Protection Association (NFPA) 403 Standard for Aircraft Rescue and Fire-Fighting Services at Airports, 2003 Edition.

[2] J.R. Butz, R.W. Marmaro, R. Tetla, K.R. Grosskopf, Fine water mists for suppression of class b fuel fires, in: Proceedings of the Halon Alternatives Technical Working Conference, Albuquerque, 1994.